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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The objectives of this program year are focused on design, fabrication, and testing of wideband guided-wave AO Bragg diffraction from surface acoustic waves in GaAs optical waveguides and conception/realization of multichannel integrated AO and EO Bragg modulator modules in TIPE microlenses-based $LiNbO_3$ and GaAs channel-planar composite waveguides with applications to signal processing and computing. The objectives have been fully accomplished.

For the first project, wideband GaAs waveguide AO Bragg cells that operate in the acoustic frequency range from 300 to 1200 MHz have been realized. Note that this represents realization of GHz GaAs waveguide AO Bragg cells for the first time, and shows that monolithically integrated optic signal processors such as RF spectrum analyzers may be fabricated in a common GaAs chip. Relevant design procedures and fabrication steps have been developed and detailed measurement on performance characteristics of the compact Bragg cells has been carried out. A paper is being prepared for publication in the near future.

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The second project relates closely to the first, namely, realization of multichannel integrated optic modulator modules in GaAs. Specifically, multichannel single-mode electrooptic cutoff modulator arrays and Bragg diffraction modulator arrays have been successfully realized in GaAs for the first time. One of the vital and remaining components toward monolithic (total) integration in GaAs is the waveguide microlens and linear lens array. For this purpose, we have, for the first time, succeeded in the fabrication of negative index-change planar *waveguide microlenses in both* $LiNbO_3$ and GaAs using ion milling. It is to be noted that the ion-milling machine used in this research was established through a DOD-University Research Instrumentation Program (AFOSR-84-0270). The waveguide lenses that have been fabricated and tested include single lenses and lens arrays of analog Fresnel, chirp grating, and hybrid analog Fresnel chirp grating types. We have obtained near diffraction-limited spot sizes and good efficiencies in such preliminary components. Ion milling has been shown to be a simple and versatile technique for fabrication of waveguide lenses in GaAs and applicable to any other substrate material. Such ion-milled waveguide lenses should facilitate realization of a variety of monolithically integrated optic device modules and circuits in GaAs and the related substrates with application to communications, signal processing, and computing. Two papers have been prepared for publication and a third paper has been accepted for presentation at the 1988 IEEE/OSA LEOS Conference.

For the third project, a number of significant advancements toward realization of hybrid integrated optic (IO) computers through fabrication of single-mode microlenses and microlens arrays in $LiNbO_3$ waveguides using a simple technique entitled titanium-indiffused proton-exchanged (TIPE) developed in-house have been made. Through this TIPE technique a variety of lens combinations may be fabricated using a single masking step. These microlenses and microlens arrays have recently been integrated with channel waveguide arrays and AO and/or EO Bragg diffraction arrays to form a variety of multichannel device modules. For example, two high-packing density multichannel integrated optic device modules were constructed in y-cut $LiNbO_3$ substrates $0.1x1.0x2.0cm^3$ in size. These two device modules represent the highest degree of integration that has been accomplished thus far, and are being used to carry out a variety of digital data processing and computing experiments, such as correlation of binary sequences and matrix multiplications.

It should also be mentioned that the ion-milling machine established through DOD-University Research Instrumentation Program (AFOSR-84-0270) was successfully used to fabricate planar microlens arrays in glass substrate for efficient coupling and excitation of multichannel waveguide arrays in such high-packing density multichannel integrated optic device modules. As indicated in the second project, this ion-milling machine was subsequently used to fabricate waveguide microlenses and linear microlens arrays in $LiNbO_3$ and GaAs substrates. Note that both technologies represents the "firsts" in the field and will play a vital role in our continued endeavor toward realization of Monolithically-Integrated Multichannel Optoelectronic Modules and Circuits for Computing, Communications, and Signal Processing.

Some of the achievements described above have been reported at the 1987 Topical Meeting on Optical Computing, 1987 International Microoptics Conference, 1987 IEEE Ultrasonics Symposium, 1988 Topical Meeting on Integrated- and Guided-wave Optics, and subsequently published in IEEE J. Quantum Electron., IEEE/OSA J. Lightwave Tech., Appl. Optics, and J. Modern Opt.

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INTEGRATED ACOUSTOOPTIC DEVICE MODULES FOR OPTICAL INFORMATION PROCESSING

INTERIM SCIENTIFIC REPORT

for

Air Force Office of Scientific Research

Grant No. AFOSR 85-0378

For the Period

1 March 1987 - 28 February 1988

Prepared By

Chen S. Tsai, Principal Investigator
Professor of Electrical Engineering
University of California
Irvine, California 92717

INTEGRATED ACOUSTOOPTIC DEVICE MODULES FOR OPTICAL INFORMATION PROCESSING

INTERIM SCIENTIFIC REPORT

Chen S. Tsai, Principal Investigator
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Table of Contents

INTEGRATED ACOUSTOOPTIC DEVICE MODULES FOR OPTICAL INFORMATION PROCESSING

INTERIM SCIENTIFIC REPORT

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I. INTRODUCTION

Guided-Wave Optics, or more commonly called Integrated Optics, is an interdisciplinary endeavor which concerns basic studies, new device concepts, miniaturization and integration of optical and optoelectronic components such as lasers, modulators, switches, lenses, prisms, couplers, detectors, etc., in a common substrate to perform a variety of scientific and engineering functions. Similar to the prevalent integrated electronic circuits, the ultimate integrated optic circuits or modules are expected to possess advantages over their discrete bulk counterparts. Some of the advantages are smaller size and lighter weight, wider bandwidth, lesser electrical drive power requirement, greater signal accessibility, higher degree of integratability, potential for batch fabrication, and ultimate reduction in cost. In fact, a variety of guided-wave electrooptic (EO) and acoustooptic (AO) devices and modules have been studied and developed using mostly the $LiNbO_3$ substrate. Such devices and modules have demonstrated some of the aforementioned advantages and are expected to provide unique applications in future single-mode optical fiber communication, and integrated optic signal processing and computing systems.

The general objectives of this AFOSR-sponsored research program are to study the basic physical mechanisms/phenomena of new and novel guided-wave AO device modules in $LiNbO_3$ and GaAs and their realization with application to wideband multichannel optical information processing.

The major projects that have been pursued during the second program year are:

1. Realization of GHz guided-wave acoustooptic Bragg cells in GaAs,

2. Conception and realization of monolithic-integrated acoustooptic and electrooptic modules in GaAlAs compounds waveguides, and applications to optical computing and signal processing, and

3. Realization of hybrid-integrated acoustooptic and electrooptic modules together with the TIPE lenses in $LiNbO_3$ composite waveguides, and applications to optical computing and signal processing.

Very significant progress has been made in each project. A detailed description of the progress and achievements is given in the following section.

II. PROGRESS AND ACHIEVEMENTS DURING PROGRAM YEAR

As indicated in the Introduction, the research objectives of this program year are focused on design, fabrication, and testing of wideband guided-wave AO Bragg diffraction from surface acoustic waves in GaAs optical waveguides and conception/realization of TIPE microlenses-based multichannel integrated AO and EO Bragg modulator modules in $LiNbO_3$ and GaAs composite waveguides with applications to signal processing and computing. The objectives have been fully accomplished.

For the first project, wideband GaAs waveguide AO BRagg cells that operate in the acoustic frequency range from 300 to 1200 MHz have been realized. Note that this represents realization of GHz GaAs waveguide AO Bragg cells for the first time, and shows that monolithically integrated Optic signal processors such as RF spectrum analyzers may be fabricated in a common GaAs chip. Relevant design procedures and fabrication steps have been developed and detailed measurement on performance characteristics of the compact Bragg cells has been carried out. A paper is being prepared for publication in the near future (publication #17).

The second project relates closely to the first, namely, realization of multichannel integrated optic modulator modules in GaAs. Specifically, multichannel single-mode electrooptic cutoff modulator arrays (publication #23) and Bragg diffraction modulator (publication #27) have been successfully realized in GaAs for the first time. One of the vital and remaining components toward monolithic (total) integration in GaAs is the waveguide microlens and linear lens array. For this purpose, we have, for the first time, succeeded in the fabrication of negative index-change planar waveguide microlenses in both $LiNbO_3$ and GaAs using ion milling. It is to be noted that the ion-milling machine used in this research was established through a DOD-University Research Instrumentation Program (AFOSR-84-0270). The waveguide lenses that have been fabricated and tested include single lenses and lens arrays of analog Fresnel, chirp grating, and hybrid analog Fresnel/chirp grating types. We have obtained near diffraction-limited spot sizes and good efficiencies in such preliminary components. Ion milling has been shown to be a simple and versatile technique for fabrication of waveguide lenses in GaAs and applicable to any other substrate material. Such ion-milled waveguide lenses should facilitate realization of a variety of monolithically integrated optic device modules and circuits in GaAs and the related substrates with applications to communications, signal processing, and computing. Two papers have been prepared for publication (publications #29 and #30) and a third paper has been accepted for presentation at the 1988 IEEE/OSA LEOS Conference (publication #31).

For the third project, a number of significant advancements toward realization of hybrid integrated optic (IO) computers through fabrication of single-mode microlenses and microlens arrays in $LiNbO_3$ waveguides using a simple technique entitled titanium-indiffused proton-exchanged (TIPE) developed in-house (see publication #11) have been made. Through this TIPE technique a variety of lens combinations may be fabricated using a single masking step. These microlenses and microlens arrays have recently been integrated with channel waveguide arrays and AO and/or EO Bragg diffraction arrays to form a variety of multichannel device modules. For example, two high-packing density multichannel integrated optic device modules were constructed in y-cut $LiNbO_3$

substrates 0.1x1.0x2.0cm^3 in size (see Figs. 1 and 2). These two device modules represent the highest degree of integration that has been accomplished thus far, and are being used to carry out a variety of digital data processing and computing experiments, such as correlation of binary sequences (see Fig. 3) and matrix multiplications (see publications #20, 21, 24, and 26).

It should also be mentioned that the ion-milling machine established through DOD-University Research Instrumentation Program (AFOSR-84-0270) was successfully used to fabricate planar microlens arrays in glass substrate for efficient coupling and excitation of multichannel waveguide arrays in such high-packing density multichannel integrated optic device modules (see Fig. 4). As indicated in the second project, this ion-milling machine was subsequently used to fabricate waveguide microlenses and linear microlens arrays in $LiNbO_3$ and GaAs substrates. Note that both technologies represent the "firsts" in the field and will play a vital role in our continued endeavor toward realization of Monolithically-Integrated Multichannel Optoelectronic Modules and Circuits for Computing, Communications, and Signal Processing.

Some of the achievements described above have been reported at the 1987 Topical Meeting on Optical Computing (publication #18), 1987 International Microoptics Conference (publication #19), 1987 IEEE Ultrasonics Symposium (publication #20), 1988 Topical Meeting on Integrated- and Guided-Wave Optics (publication #24), and subsequently published in IEEE J. Quantum Electron., (publication #23), IEEE/OSA J. Lightwave Tech., (publication #27), Appl. Optics (publication #26), and J. Modern Opt., (publication #28).

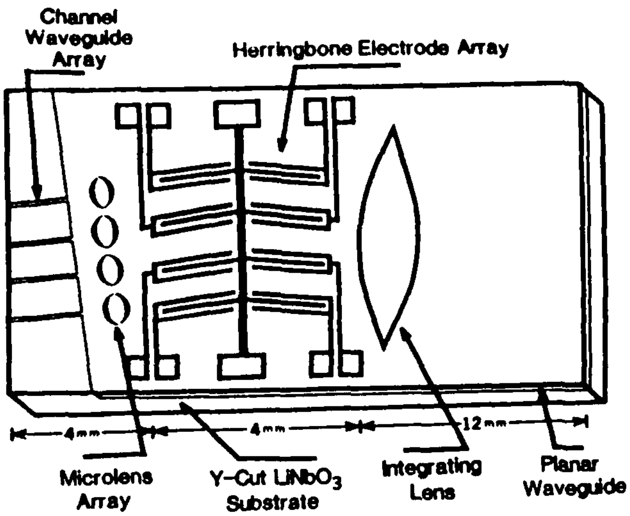

Fig. 1

Multichannel Integrated Electrooptic Device Module

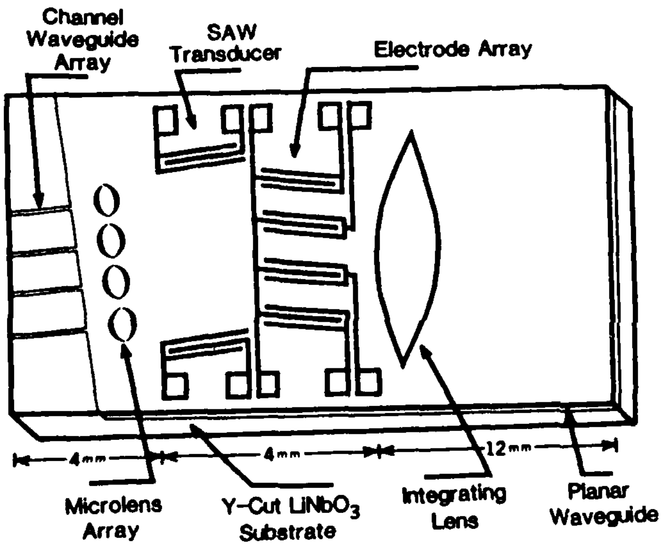

Fig. 2

Multichannel Integrated Acoustooptic-Electrooptic Device Module

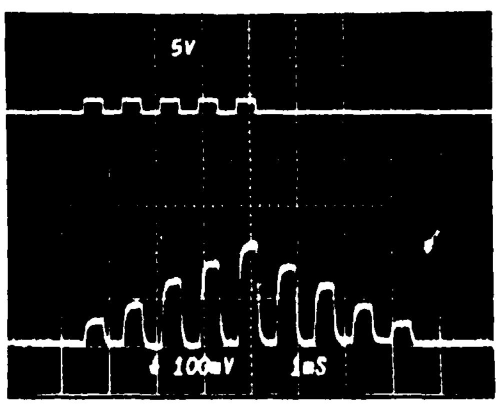

Fig. 3 (a)

Auto-Correlation Waveform of 10-bit Binary Sequence

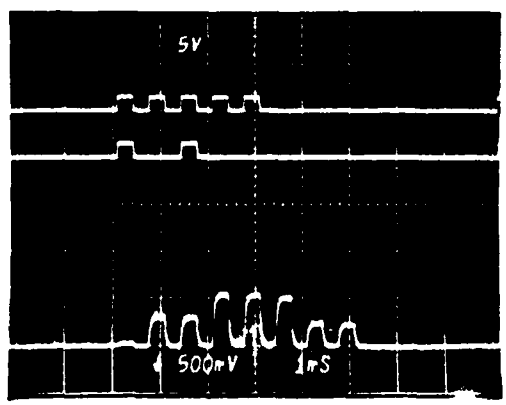

Fig. 3 (b)

Cross-Correlation Waveform of Two 10-bit Binary Sequences

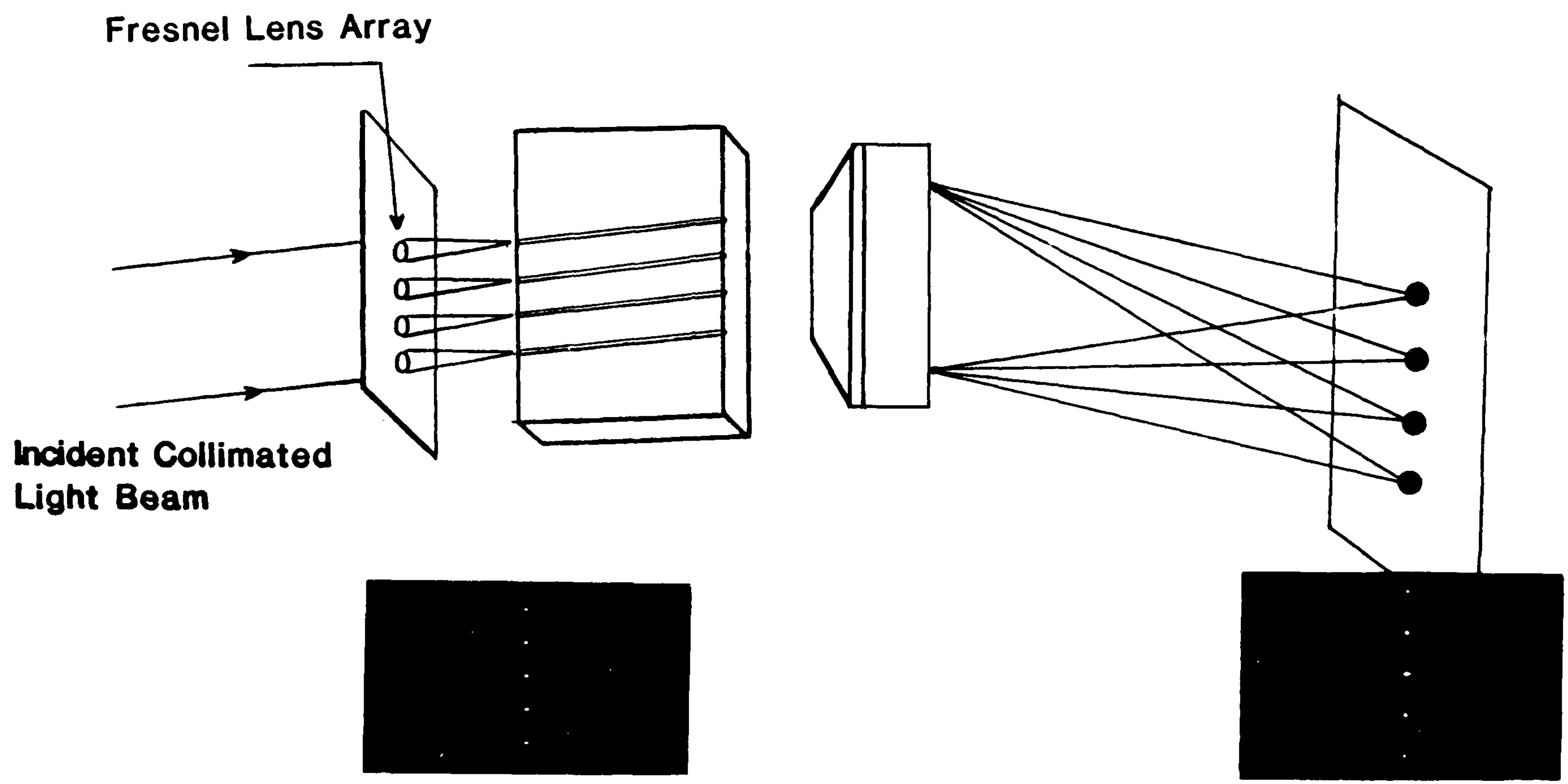

Fig. 4 Excitation of Channel Waveguide Array in $LiNbO_3$ Using Planar Microlens Array

III. RESEARCH IMPACTS AND INTERACTIONS WITH OTHER INVESTIGATORS

1. Realization of both wideband GaAs acoustooptic Bragg cells and TIPE microlens-based integrated optic modulator modules as well as demonstrated applications in computing, communications, and RF signal processing have already generated a significant interest in the U.S. and abroad. For example, this principal investigator was bestowed the prestigious IEEE Distinguished Lecturer Award for 1986-87 to lecture on "Guided-Wave Acoustooptic Interactions, Devices, and Applications." This principal investigator was invited to deliver 55 lectures at technical societies, universities, and industrial laboratories in the U.S. and abroad including West Germany, France, Switzerland, Japan, and China to speak on this emerging technology. During these lectures a great deal of interest was expressed by the attendees in the multichannel integrated optic device modules referred to above.

2. In regard to the Guided-Wave Magnetooptics research that was conducted in earlier years under the sponsorship of this AFOSR program, the impacts of research are increasingly felt. For example, this principal investigator was asked to present an invited paper on the subject at the 1987 International Magnetics Conference in Tokyo, Japan (see publication #16). As evidenced at the conference this particular subject has been picked up for further research in a number of foreign countries, most notably Japan, Russia, and China.

3. The TIPE waveguide lenses and the basic channel-planar composite waveguide structures that have been investigated under this AFOSR program are being utilized to construct a variety of compact integrated optic device modules with applications to multichannel communications, computing and signal processing. Furthermore, such combined TIPE microlens-composite waveguide structures are starting to create impacts in the U.S. and abroad. For example, Professor Dimetri Psaltis of Cal Tech. is using such combined device structure for implementation of general optical linear transformations, e.g. optical matrix-vector multiplication. In the meantime, Dr. John Caulfield of the Center for Applied Optics, University of Alabama, is exploring the potential of the same device structure for realization of neighborhood image processors and optical interconnects in neural networks. Also,

many foreign scientists and engineers expressed interests in the combined device structures during the IEEE Distinguished Lecture tour abroad by this principal investigator. For example, I was asked to present an invited paper on the subject at the First Microoptics Symposium that was held in Japan last year (see publication #19), and researchers at Hoya Co. in Japan are using the same device structure for realization of optic device modules similar to those developed at my laboratory.

4. The combined device structure has also for some time attracted the attentions of Drs. David Pelka and Thomas Jannson of Physical Optics Corporation, Torrance, California. In this connection, this principal investigator recently conceived the idea of using the combined device structure for realization of optical interconnects by inserting a multiplicity of dynamic diffraction holograms in the planar waveguide region. By means of a page-oriented holographic memory that is placed above and separated from the waveguide structure, the optical signal at any of the input channels (ports) may be routed to any of the output channels by activating an appropriate set in the multiplicity of holograms. Physical Optics has recently developed organic film-based volume holograms that have shown very high diffraction efficiency. Furthermore, such organic material has also been used to make multi-layer or stratified volume holograms. Through such multi-layer holograms the dimension perpendicular to the waveguide substrate may be utilized to construct optical interconnects. Thus, in addition to pursuing the research topics described in the original proposal, the optical interconnects project described above will be explored during the proposed no-cost extension period.

IV. PUBLICATIONS RESULTING FROM AFOSR SUPPORT

A. Recent Publications

1. C. S. Tsai, D. Young, W. Chen. L. Adkins, C. C. Lee, and H. Glass, "Noncollinear Magnetooptic Interaction of Guided-Optical Wave and Magnetostatic Surface Waves in YIG/GGG Waveguides," Appl. Phys. Lett., Vol. 47, pp. 651-654 (Oct. 1985).

2. C. S. Tsai, D. Y. Zang, and P. Le, "An Integrated Acousto-optic Bragg Modulator in $LiNbO_3$ Channel-Planar Composite Waveguides," Proc. of 5th International Conference on Integrated Optics and Optical Fiber Communication and 11th European Conference on Optical Communication, pp. 125-128, Oct. 1-4, 1985, Venezia, Italy.

3. D. Y. Zang, P. Le, and C. S. Tsai, "An Integrated Acoustooptic Bragg Modulator in a $LiNbO_3$ Channel-Planar Composite Waveguide and Its Applications," IEEE 1985 Ultrasonics Symposium, Technical Digest, pp. 117-118, Oct. 16-18, San Francisco, California.

4. W. Chen, D. Young, and C. S. Tsai, "Mode-Conversion of Guided-Optical Waves Through Noncollinear Interaction with Magnetostatic Surface Waves - Theory and Experiment," IEEE 1985 Ultrasonics Symposium, Technical Digest, p. 146, Oct. 16-18, San Francisco, California.

5. C. S. Tsai, "Integrated Optic Device Modules for the Space Applications," Proc. of the Society of Photo-Instrumentation Engineers Conference on Optoelectronics and Laser Applications in Science and Engineering, pp. 19-24, Jan. 1986, Los Angeles, California, SPIE, Vol. 616 (Invited Paper).

6. C. J. Lii, C. S. Tsai, and C. C. Lee, "Wideband Acoustooptic Bragg Cells in GaAs-GaAlAs Waveguides," IEEE J. Quantum Electron., Vol. QE-22, Special Issue on Integrated Optic Circuits, pp. 868-872 (June 1986).

7. C. J. Lii, C. S. Tsai, and C. C. Lee, "A Compact Miniaturized Acousto-Optic Bragg Cell in GaAs-GaAlAs Waveguides," 1986 Topical Meeting on Integrated- and Guided-Wave Optics, Feb. 26-28, 1986, Atlanta, Georgia, Technical Digest, IEEE Cat. No. 86CH2264-0, pp. 58-59.

8. W. Chen, D. Young, and C. S. Tsai, "Theory and Experiment on Guided-Optical Wave Mode-Conversion Through Noncollinear Interaction with Magnetostatic Surface Waves in YIG-GGG Waveguides," 1986 Topical Meeting on Integrated- and Guided-Wave Optics, Feb. 26-28, 1986, Atlanta, Georgia, Technical Digest, IEEE Cat. No. 86CH2264-0, pp. 28-31.

9. C. S. Tsai, D. Young, and W. Chen, "Interactions between Optical Waves and Magnetostatic Surface Waves in Ferromagnetic Waveguides," Proc. of International Symposium on Surface Waves in Solids and Layered Structures, Vol. III, pp. 100-115, July 1-4, 1986, Novosibirsk, USSR (Invited Paper).

10. C. S. Tsai, "$LiNbO_3$-Based Integrated Optic Device Modules for Optical Communications, Signal Processing and Computing," 1986 Conference on Lasers and Electro-Optics, June 9-13, 1986, San Francisco, California, Technical Digest, IEEE Cat. No. 86CH2274-9, pp. 44-46 (Invited Paper).

11. D. Y. Zang and C. S. Tsai, "Titanium Indiffused Proton Exchanged Waveguide Lenses $LiNbO_3$ for Optical Information Processing," Special Issue on Optical Computing, App. Opt., Vol. 25, pp. 2264-2271 (July 1986).

12. C. J. Lii, C. S. Tsai, C. C. Lee, and Y. Abdelrazek, "Wideband Acoustooptic Bragg Cells in GaAs Waveguides," Proc. of 1986 IEEE Ultrasonics Symposium, No.v 1986, Williamsburg, Virginia, IEEE Cat. No. 86CH2375-4, pp. 429.433.

13. C. S. Tsai, "Titanium-Indiffused Proton-Exchanged Microlens-Based Integrated Optic Bragg Modulator Modules for Optical Computing," Optical and Hybrid Computing, SPIE, Vol. 634, pp. 409-421, Jan. 1987 (Invited Paper).

14. C. S. Tsai, "Integrated Acoustooptic Device Modules for Communications, Signal Processing, and Computing," 7th Ultrasonic Electronics Symposium, Dec. 8-10, 1986, Kyoto, Japan, to appear in Japanese Journal of Applied Physics, 1987, (Invited Paper).

15. D. Young, W. Chen and C. S. Tsai, "Tunable Wideband Guided Wave Magneto-optic Modulator Using Magnetostatic Surface Waves," presented at SPIE Meeting, Jan. 1987, Los Angeles, California, Proc. SPIE, Vol. 753, (Invited Paper).

B. Publications During Program Year

16. C. S. Tsai, D. Young, W. Chen, H. Glass, and L. Adkins, "Wideband Interactions Between Optical Waves and Magnetostatic Surface Waves in a YIG-GGG Waveguide," Proc. of 1987 International Magnetics Conference, p. GC-07, April 14-18, 1987, Tokyo, Japan (Invited Paper).

17. Y. Abdelrazek, and C. Tsai, "GHz Acoustooptic Bragg Cells in GaAs Waveguides," (to be published).

18. D. Y. Zang, P. Le, and C. S. Tsai, "Integrated Electrooptic Bragg Modulator Modules for Optical Computing," Second Topical Meeting on Optical Computing, March 16-18, 1987, Incline Village, Nevada, Technical Digest Series, Vol. 11, (Optical Society of America) pp. 193-196.

19. C. S. Tsai, "Multichannel Integrated-Optic Device Modules for Optical Processing," 1st International Microoptics Conference, Technical Digest, Tokyo, Japan, pp. 194-195, October 1987 (invited paper).

20. P. Le, D. Y. Zang, G. D. Xu, and C. S. Tsai, "An Integrated-Optic Digital Correlator Module Using Acoustooptic and Electrooptic Bragg Diffractions in $LiNbO_3$," Proceedings of the 1987 IEEE Ultrasonics Symposium, 87CH2492-7:467-470, October 1987.

21. C. S. Tsai, "Integrated-Optic Device Modules for Computing and Signal Processing," Proceedings of the 21st Annual Asilomar Conference on Signals, Systems, and Computers, IEEE, Pacific Grove, California, pp. 467-473, November 1987 (invited paper).

22. C. S. Tsai, "Integrated Acoustooptic Device Modules for Communications, Signal Processing, and Computing," Japanese Journal of Applied Physics, 26:19-25, 1987 (invited paper).

23. R. T. Chen and C. S. Tsai, "GaAs-GaAlAs Heterostructure Single-Mode Channel-Waveguide Cutoff Modulator and Modulator Array," IEEE Journal of Quantum Electronics, Special Issue on Electrooptic Materials and Devices, QE-23:2205-2209, December 1987.

24. C. S. Tsai, D. Y. Zang, and P. Le, "Multichannel Integrated-Optic Device Modules in $LiNbO_3$ for Digital Data Processing," Technical Digest of 1988 Topical Meeting on Integrated and Guided-Wave Optics, Santa Fe, New Mexico, pp. 200-203, March 1988.

25. C. S. Tsai, "Guided-Wave Acoustooptic Devices and Applications," Proceedings of Physics in Microoptics Conference, Tokyo, Japan, pp. 59-70, May 1988 (invited paper).

26. P. Le, D. Y. Zang, and C. S. Tsai, "Integrated Electrooptic Bragg Modulator Module for Matrix-Vector and Matrix Multiplications," Applied Optics, Special Issue on Optical Computing, 27:1780-1785, May 1988.

27. X. Cheng and C. S. Tsai, "Electrooptic Bragg-Diffraction Modulator in GaAs-GaAlAs Heterostructure Waveguide," Journal of Lightwave Technology, Special Issue on Integrated Optics, 6:809-817, June 1988.

28. C. S. Tsai, "Integrated-Optic Device Modules in $LiNbO_3$ for Computing and Signal Processing," Journal of Modern Optics, June 1988 (in press, invited paper).

29. T. Q. Vu, J. Norris, and C. S. Tsai, "Formation of Negative Index-Changes Waveguide Lenses in $LiNbO_3$ Using Ion Milling," Optics Letters, 1988 (in press).

30. J. Norris, T. Vu, and C. Tsai, "Planar Waveguide Lenses in GaAs Using Ion Milling," (to be published).

31. T. Vu, J. Norris, and C. S. Tsai, "Negative Index-Change Waveguide Lenses in $LiNbO_3$ Using Ion Milling," (accepted for presentation at IEEE/OSA Conference, Nov. 2-4, 1988, Santa Clara, CA).

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VI. ADVANCED DEGREES AWARDED

A. Ph.D. Dissertations

1. C. J. Lii, "Wideband Acoustooptic Bragg Diffraction in GaAs Waveguides," September 1986.

2. W. Chen, "Guided-Wave Acoustooptic Interactions in Spherical Waveguides," June 1987

3. X. Cheng, "Film Material Characterization and Electrooptic Bragg Modulator," September 1987.

4. D. Y. Zang, "TIPE Microlenses and Microlens Arrays, and Multichannel Integrated Optic Device Modules," October, 1988.

B. M.S. Theses

1. J. Norris, "Negative Index-Change Analog Fresnel Lens for Integrated Optics," June 1988.

2. T. Vu, "Negative Index-Changed Hybrid Lens of Chirp Grating and Analog Fresnel Types on $LiNbO_3$ and GaAs Planar Waveguides," June 1988.